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PROPOSAL OF MULTIDISCIPLINARY APPROACH TO THE PREDICTION OF MINING INDUCED GEODYNAMIC PROCESSES

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Abstract: At present the mining in the deep Kladno-2 Coal Mine has been already ceased with the exception of .the pit-safety pillar having an area of 400 x 400 m^2. The excavated coal seam in this mine is exposed to very strong rockburst danger. The rockburst prevention requires recording of all rockburst events and also assessment and verification of methods of predicting the rockbursts. The investigation of forerunners must be based on the monitoring of complex processes in rock mass. The main purpose is to learn about the mechanics of rockburst foci. By describing the processes in rockburst source zones one can also contribute to the understanding of some problems of natural earthquake prediction.

Key words: earthquake; rockburst; prediction; modelling; precursors; seismoacoustics; geoelectrics; geodynamics

1. INTRODUCTION

We understand, under induced geodynamic processes, the following:

- deformations and inclinations of mine openings (shafts, long walls),
- deformations, slips and inclinations in the overburden rock mass as well as on its surface,
- outbursts of gases and liquids in mine openings,
- rockburst events.

These phenomena result from the interaction between the tectonophysical parameters of rock mass (initial stress-strain state) and the parameters of mine working (shape, size and advance rate, volume and frequency of blasting work and the orientation of long mine openings relative to tectonic faults).

Natural tectonophysical conditions of rockburst occurrence are similar to those of shallow intraplate tectonic earthquakes. It is this very analogy that enables the rockbursts to be regarded as models of shallow earthquakes (Buben and Rudajev, 1977). From this point of wiev, earthquake prediction can make use of results of rockburst investigations.

The mining activity provoking relatively quick changes of the structure and stress-strain state of rock affects primarily the rate of brittle fracturing and the occurrence of rockburst phenomena. This makes it possible to acquire a sufficiently large data set within a sufficiently short time interval and to verify the methods and results of seismostatistical prognoses.

In comparison with earthquakes, the position and volume of rockburst-source zone is known for a sufficiently long time beforehand, which enhances the economy and productivity of investigation. The source zone is accessible by mining shafts, which considerably facilitates geophysical, geological, geodetic and statistical investigations carried out simultaneously, the variety of input data being monitored not only on the surface but also right within the source zone.

The study of rockbursts and rock property changes as a function of stress changes in underground mines could further the understanding of pre-failure processes. Rockbursts reaching the magnitude up to about $M = 2$ are triggered by the excavation process. Consequently, one has an idea of when and where a future rockburst will happen. The study of rockbursts could therefore be called a semi-controlled experiment. This opportunity to study precursors and earthquake source processes has been utilized since the sixties in a deep coal mine near Kladno (X = 1 031 050; Y = 765 550).

2. PREVIOUS RESEARCH INTO ROCKBURSTS IN COAL MINE KLADNO-2

According to the valid Mine Safety Code (Czech Mine Supervisor Office, 1991) the coal seam excavated in the Kladno-2 Coal Mine is exposed to the first-order rockburst danger. The overlying strata are formed from sandstones, conglomerates and claystones. The presence of a thick (70 m), brittle and relatively strong bed in the roof (having compressional uniaxial strength of about 10 MPa and Young's elasticity modulus up to about 2 GPa) greatly increases the danger of rockbursts induced by mining activity. Rockburst prevention requires, beyond adequate safety measures, special winning techniques that either avoid the dangerous accumulation of rock stresses or contribute to a controlled displacement of the accumulated stresses. Both solutions require the monitoring of the development of rock stresses in the wider foreground of the winning front with an accuracy unattainable by means of the previously used techniques.

The prognoses must be based on monitoring and verifying rockburst forerunners. The forerunners which can be observed by colliers without making use of any instrument are the following:

- visible slipping/cracking of timbering groins,
- hardening of the coal substance and its shooting out of the walls, and
- unusual delay of cover caving in the openings.

The prognoses must be made on the basis of site-specified empirical knowledge.

Another, special forerunner, mentioned also in the Mine Safety Code, is an unfavourable result of rockburst prediction. It is evident that each scientific prediction must be based on acquisition and processing of at least the following data:

- Actual mining technology and local tectonic structure of the surrounding rock mass, and evidence of blasting work in the past as well as in the future.
- Short-time and rheological moduli of elasticity in the coal seam and in the surrounding rock mass.
- Distribution of the actual rate of convergence, slipping, tilts and subsidence of the rock mass surrounding the mining openings.
- Monitoring of the variations of stress-strain state of the surrounding rock mass.
- Recording of seismoacoustic impulses.
- Monitoring of the occurrence of rockbursts (time, site and size (energy)).

The study of rockbursts in the Kladno-2 Coal Mine started already at the end of the fifties. Local seismic station Vinařice has been operating since 1961. Such a long series of rockburst recording is unique in the world. This seismic monitoring has confirmed that the mine is exposed to strong rockbursts.

The seismological methods of investigating rockbursts, developed in the Kladno-2 Coal Mine, have later been applied in other districts (Příbram, Ostrava) and Lower Silesian (Poland) districts.

The methodologies involve:

- Seismic monitoring (Rudajev and Buben, 1964, 1967; Rudajev, 1966; Buben and Rudajev, 1979; Rudajev *et al.*, 1977).
- Location of rockburst foci (Buben and Rudajev, 1965; Přibyl and Rudajev, 1969; Rudajev *et al.*, 1965; Rudajev and Přibyl, 1969, 1971).
- Type analysis of rockbursts (Buben, 1964).
- Identification of similarities between time and space distribution functions of rockbursts and of natural earthquakes (Buben and Rudajev, 1977; Rudajev, 1966; Riznichenko *et al.*, 1967).
- Classification of rockbursts on the basis of local clustering and of energy-flow variations (Rudajev, 1966, 1971).
- Fault-plane solutions based on a newly introduced shear-implosive model (Fučík and Rudajev, 1973, 1979a, b, 1980; Kozák *et al.*, 1985; Rudajev *et al.*, 1986; Rudajev and Šílený, 1985).
- Predictive extrapolation of rockburst series based on correlations with other geodynamic processes (Rudajev, 1969; Rudajev and Buben, 1973; Rudajev and Fučík, 1976, 1979, 1982; Rudajev *et al.*, 1976).

3. PROPOSAL OF THE FUTURE RESEARCH

At present, a rare opportunity comes up in the Kladno-2 Coal Mine. The mining in most fields has alredy been ceased with the exception of the pit safety pillar, i.e. an area of about 400 x 400 m. This brings a substantial simplification of boundary and initial conditions for modelling and analytical research:

(a) The geological situation of the pillar is relatively simple and well known.

(b) Only one, almost horizontal seam (thickness of 9 m) is deposited at a depth of about 500 m.

(c) The overlying strata are formed from sandstones, conglomerates and claystones.

(d) The values of horizontal and vertical stress components are nearly the same. This is obviously a consequence of residual tectonic stress state, connected with the tertiary activity of the local volcano Vinařická hora Mt.

(e) The mine field and also the investigated safety pillar are affected by steeply dipping (38°) tectonic faults. Except for the two vertical shafts (Mayrau and Robert), the hanging wall of the pit safety pillar has not been affected by any previous mining and rockburst activity.

The in situ investigation and monitoring in the safety pillar started in the second half of 1992. It includes modelling and theoretical solutions complemented by special methods of seismics, geodesy and geomechanics.

The main purpose of our ongoing investigation is to improve the up-to-date reliability of rockburst prognoses and predictions. The methodology is based on the synthesis of interdisciplinary data.

The practical impact is seen in the possibility of increasing the safety of mine working. The scientific contribution is seen in understanding the physical processes in seismic source zones. This can contribute also to the prediction of natural earthquakes.

4. SEISMIC RECORDING OF ROCKBURSTS

A local seismic array of four seismometers was built in June 1992. Three seismometers (Mark SM-3, $T = 2$ s, $D = 0.6$) are situated on the surface and one seismometer is underground at a depth about 500 m. The seismometers/preamplifiers are connected with the central recording computer by mine telephone cables. The triggering level of the recorder is adapted to the local stationary seismic noise which attains the amplitudes of about 5 - 10 μm/s in the frequency range of 1 - 30 Hz.

During the second half of 1992, about 125 rockbursts of three distinguishable types were recorded and preprocessed (Růžek, 1992). Most foci were located to or near the safety pillar. As the first approximation of the seismic model a half-space with isotropic seismic velocity $V_P = 2.1$ km/s was used. The relative local magnitudes did not exceed the value $M_L = 1.8$, the minimum value being $M_L = 0.3$. The scatter of foci is considerable and the accuracy of location was evidently not satisfactory.

At the beginning of 1993, the array shall be extended to 15 seismic channels. In the recording centre the digital triggered system Lennartz Mark LE-5800 will be used. Original software was developed (Bucha, 1992; Fischer, 1992; Růžek, 1992) for the following problems:

(A) Preprocessing the records and determining basic parameters of rockbursts, i.e. focal time, site and size (magnitude). - Any scientific prediction of rockbursts only deserves this name if these quantities are carefully specified. To minimize the uncertainty in location the seismic model of the whole source zone must be constructed with the maximum possible accuracy. Great attention must be paid to the research of non-linear mechanics which, no doubt, takes place in the near-focus zone (Kozák, 1992).

(B) Solution of fault-plane orientation based on construction of nodal lines. Determination of the type of faulting, size and shape of the focus, and of the amount of elastic displacement in the source volume. Determination of seismic moments and values of stress drop. Evaluation of the radiation pattern of rockburst foci.

(C) Spectral analysis of rockburst records. - Two main problems are encountered here: (a) determination of the spectrum modulation-depth which depends on the rockburst magnitude (Kozák, 1992), and (b) determination of time variations of quality factor Q which may be considered as precursors of rockbursts (Fischer, 1992).

(D) Distribution of rockbursts in time, site and size.

The following statistical functions play a great role in verifying the hypotheses of rockburst origin in the individual source zones:

(a) Autocorrelation structure of the time series of rockburst energies and of interoccurrence intervals.

(b) Variations of the rate of seismic energy flow which corresponds to the rate of cumulative seismic moment M_0 of rockbursts.

(c) Spatial clustering of foci (around mine workings or around tectonic faults).

5. SEISMOACOUSTIC PRECURSORS

The UGA-15 digital 15-channel monitoring centre for recording seismoacoustic impulses is being built underground (Kořínek, 1992). Five three-component geophones (f_0 = 30 Hz, D_0 = 0.6) are inserted into boreholes (depth about 3 m) in the hanging wall. Spontaneous as well as man-made seismoacoustic events will be recorded in the frequency band of 30 Hz - 2 kHz. The recording computer operates in the triggering mode and forms data sets which are stored in disc memory.

5.1. Seismoacoustic foreshocks

Seismoacoustic emission (impulses) can appear as a symptom of advanced state of brittle fracturing which could take place in the overlying hard sandstone layer. Therefore the maximum signal-to-noise ratio should be attainable by placing the geophones in the high overburden, i.e. at a distance of a few tens of metres above the coal seam. However, the technically practicable length of boring is only about 3 m. Therefore, most seismoacoustic events will have focal distances up to 100 m. Therefore the dominating frequencies of vibration are expected to be between 0.3 kHz and 2 kHz.

The most difficult problem is the discrimination between disturbing (technogenic) and useful (man-made as well as spontaneous) impulses. Two most effective methods are time-selective and site-selective recording.

Time-selective recording makes use of only those impulses which occur at certain hours when the mining is interrupted or substantially reduced (e.g. during night shifts). Site-selective recording only intercepts impulses originating inside the prescribed source volume in the overlying strata. This discrimination is made automatically by means of software based on the time differences of *P*-wave onsets on geophones.

5.2. Variations of the seismoacoustic transfer function

Roadways and stopes can pass through sections of the seam where coal has been fractured or crushed, so that its strength (bearing capacity) is degraded. In such segments, very strong devastations can occur as a consequence of rockbursts having foci in the neighbourhood. The fractured state of the coal seam can be detected as an anomalous (high) attenuation of amplitudes of seismoacoustic waves.

On the other hand, the process called "hardening" of the coal substance in the seam can be indicative of its marginal state of compression. This hardening can also be detected by means of seismoacoustic response function (low value of attenuation at higher frequencies).

Both anomalies of seismoacoustic response function (SRF) can be determined by cospectral analysis of seismoacoustic waves passing throuh the zone under investigation.

For investigations of SRF variations with the actual site of extraction, a simple and quick "short base-line" method seems to be the most feasible. Seismoacoustic inpulses are initiated by hitting rock bolts, placed in the seam, by hammer (about 15 blows). The receiving geophones are oriented horizontally 4 m apart. Signals are sent up from the mine to the recording instrument through a standard mine telephone cable. The piezo-geophones, built in cylindrical metal housings together with the preamplifiers, are inserted into boreholes (about 1 m deep) drilled into the sidewall of the roads along the midline of the seam. The spectral analysis can be made immediately using the software for digital spectrum analysing by means of PC. Exploration in the mine need not be stopped during the measurements since they can be made during the change of shifts and/or during preparation of boreholes for blasting works.

The described "short base-line" seismoacoustic method can be applied daily as an convenient and reliable tool for monitoring the actual development and displacement of stress-fracturing in mine workings.

Seismoacoustic "medium base-line" method (up to 100 m) makes use of the standard seismoacoustic array as well as of standard blasting work used in mining. Mining blasts are usually fired at the end of shifts. The whole charge volume of explosives is of the order of kilogramms, but there are partial charges blasted-off step by step with time lags of about 20 ms.

One of the 15 geophones connected to the underground seismoacoustic array (UGA-15) operates as a "moving" pick-up having a very robust (strong motion) construction. This geophone must be moved forward at the same pace as the advance of the coalface. It must be placed in the vicinity (several metres) of the explosives. The records of "focal" vibrations are used for the accurate determination of the focal time as well as of vibration spectra.

Some of these exploration blasts can be recorded with acceptable signal-to-noise ratio not only by the underground seismoacoustic array but also by the seismographs of the local seismic array. By processing these records one can evaluate the variations of transfer functions in more directions (subhorizontal and subvertical). The "long base-line" (about 500 m) seismic response variations can appear as a consequence of the fracture process spreading up to the high overlying strata.

The sites of exploration blasting can be determined with high accuracy (about 1 m), which, together with accurate determination of focal times, can be used for improving the accuracy of the seismic model of rock mass.

5.3. Seismoacoustic aftershocks

Exploration blasting very often provokes aftershocks, i.e. seismoacoustic events or even rockbursts. This offers an opportunity to study the actual stress state in the rock by means of fault-plane and stress-drop solutions.

It is well known that the seismoacoustic aftershocks can be provoked not only by exploration blasting but also by near-focus rockbursts. The probability of occurrence of a next rockburst increases substantially when the surrounding rock mass attains the state of ultimate stress and unstable growth of microfractures. It is assumed that even this critical state manifests itself by the occurrence of aftershocks.

6. ROCKBURST PRECURSORS

The mining in the safety pillar will induce geodynamic processes as well as rockbursts. The changes in the strain-stress state of rock can occur not only in the neighbourhood of the future focus but also at certain distances from it. As the appearance of such precursors is associated with changes in the stress-strain state of rock, all precursors can be divided into two large sets:

(1) One set includes those precursors which can be derived from direct measurements of strain (geodetic, tiltmeter and strainmeter methods).

(2) The other set includes processes arising as transformation of strain into some kind of signal (e.g. electric). This transformation depends on the property of the medium called tensosensitivity. It may be hypothesized that the transformed precursors typically have more complex conditions of formation and distribution than the strain precursors.

In order to assess reliable rockburst precursors, the following processes will be subjected to detailed testing:

6.1. Convergence of the walls of horizontal and vertical shafts

A method based on repeated close-range photogrammetry of the vertical shaft was developed (Vencovský, 1992).

6.2. Inclination and subsidence of the earth's surface measured by hydrostatic water-tube levels

The least measurable water level differences of 0.05 mm and the length of the measuring base 30 m allow us to expect tilt measurement accuracy of 0.07". In order to reach the necessary isothermal state, the whole instrument (two bases perpendicular to each other and three level pick-ups) must be situated in an underground adit.

6.3. Horizontal movements of the earth's surface

The two following methods were developed:

(a) Airborne photogrammetry. To verify this method stereophotogramms were taken from a helicopter hanging at a height of about 500 m. The method seems to be not yet accurate enough (expected erorrs about 10 cm). On the other hand, it can be very useful for detecting morphostructural lineaments related to the surface outcrops of tectonic faults being active in the recent time period (10^6 years).

(b) Laser-strain interferometric extensometry. Instrument LA 1000 made by Metra Blansko is capable of recording slow variations of the distance between two pillars (about 30 m) bearing a laser source and a reflector, respectively. The expected accuracy of distance variation measurements is of the order of 80 nm/10 m. This computerized instrument (which, however, must be energized ny the mains) was situated in a near-to-surface wall. The long-time accuracy of measurements will deteriorate due to variations of temperature, pressure and humidity of the ambient air.

6.4. Activity of a tectonic fault

A tectonic fault (throw of about 10 m) disturbing the safety pillar is rather well accessible via a horizontal shaft at a depth of 500 m. The present state of its (natural and/or mining induced) slipping activity will be monitored using methods of engineering geology and experimental geomechanics. Measurements of changes in the stress state of rock mass in the neighbourhood of the fault will be made by the method of stress-releasing (overcoring), and by the method based on measuring the variations of friction of borehole facing.

6.5. Ultrasonic wave velocity variations

These variations can be indicative of the changes of stress in rock mass induced by mining at distances of about 50 m. The continuous recording of ultrasonic velocity variations is based on digital evaluation of the phase lag between continuous vibrations at the transmitter and those at the receiver, both being installed in boreholes (base-line of about 5 m).

The interpretation of recorded variations is based on the assumption that a close relation exists between rock stresses and the velocity of ultrasonic waves propagating through the rock. By means of continuous ultrasonic velocity measurements along a stable base-line one can determine the time-dependent stress changes that occur in the the rock.

6.6. Electric resistivity variations

Because rocks are essentially semi-conductors, their resistivity is very sensitive to the presence of pore fluids and to the number of pores and cracks per unit rock volume. Even with constant volume of pore fluids the resistivity can drop drastically by increasing the number and dimensions of cracks. It seems that a film of pore fluid on the crack walls is sufficient to act as a conductor. If such conductors are interconnected due to an increase in crack density the resistivity decreases.

The electrical well logging method has been applied in a shallow observation borehole (depth 20 m) near the Yamasaki fault (Yoshino and Yukutake, 1985). An earthquake of $M = 5.6$ occurred about 3 km of the borehole. It was found that the apparent sensitivity had changed by about 2% during one day before and one day after the earthquake.

Therefore we assume that resistivity measurements may be a sensitive technique for detecting premonitory changes in rock mass (Wyss, 1981).

The well-known four-electrode method has been adopted for our repeated measurements of the electric resistivity of the overburden sandstone bed. Two current electrodes are placed about 20 m apart. Potential is measured between two electrodes situated in Schlumberger's position. All electrodes are inserted into boreholes.

If this geoelectric method is used in mine conditions (with storng disturbing currents caused by mine electric traction), the primary and secondary signals must be filtered to eliminate the linear distortions (offset of the electrodes and amplifiers), drifts, long-period tellurics, etc. Further signal-to-noise improvement can be achieved by multifold summation, or by means of a phase detector (Yamazaki, 1967, 1968).

6.7. Telluroelectric currents

According to Varotsos *et al.* (1982) transient decreases of the geoelectric currents occur before each erthquake in Greece with a lead time of 6 - 8 hours. The anomalies of 0.5 - 30 mV were measured on geoelectric lines of 50m length.

Two geoelectric lines perpendicular to each other (for recording components E_x and E_y of electric currents) were established on the site of the underground seimoacoustic array. The electrodes were inserted into holes (depths 3 m) bored horizontally from the sidewalls of the shaft. The length of the lines is about 3 m. The electrodes are connected to high-precision operational amplifiers. After passing through a bandpass filter (0.003 - 0.3 Hz), the potential difference is displayed on a chart recorder. The sensitivity of the whole channel has been set at the value of 10^{-5} V/mm.

The electromagnetic component H_z is sensored by an electromagnetic antenna, i.e. a coil. The frequency band of this channel corresponds to that of the electric channels.

It is assumed that electromagnetic emission with considerably high frequencies (from 20 kHz up to the first MHz) can be recorded not only near the future earthquake source, but also far from it. According to Monakhov (1979) an empirical relation $\lg n\ r = M$ holds beween radius r [km] of the zone of detectable precursors and magnitude M. However, the physics of such experimentally determined volume of the source zone has not been satisfactorily explained up to now. Inside the whole source zone, deformation processes perhaps take place with intensity sufficient for initiating the transformed precursors.

To verify the possibility of detecting similar electromagnetic precursors also in the case of rockbursts, the set of sensors contains also a magnetic ferrite antenna with sensitivity adjusted to receive the above-mentioned high-frequency signals.

7. CONCLUSIONS

The geodynamic phenomena induced by mining in the isolated safety pillar at the deep Kladno-2 Coal Mine, will be investigated in their complex.

This research, started in the second half of 1992, represents a middle-scale model research in seismicity and earthquake prediction. The investigations are aimed at the determination of the distribution of rockburst foci in time, site and size (magnitude) and at the understanding of the general laws of pre-seismic processes in the seismic source zone. Results of this modelling will also contribute to the research into natural seismicity.

The main purpose of this research is to describe the mechanics of rockburst foci more precisely on the basis of all the geotechnic, mining-technique and geophysical data.

The practical purpose is to predict the site, time and size of strong mining induced geodynamic phenomena with an impact on increased safety of mine workings, shafts and surface objects.

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